Early warning GBInSAR-based method for monitoring Volterra (Tuscany, Italy) city walls

Early Warning GBInSAR-Based Method for Monitoring Volterra (Tuscany, Italy) City Walls

Fabio Pratesi, Teresa Nolesini, Silvia Bianchini, Davide Leva, Luca Lombardi, Riccardo Fanti, and Nicola Casagli

***Abstract*—Ground-based synthetic aperture radar interferometry (GBInSAR) remote sensing technique has been repeatedly proved an effective tool for monitoring built environment affected by structural and geological criticalities. In this paper, it is described how this technique can be successfully applied for early-warning procedures and detection of ongoing deterioration processes on archeological and cultural heritage sites. An integrated approach of GBInSAR and terrestrial laser scanner (TLS) technologies was performed on Volterra test site (Tuscany, Italy), where a sudden collapse of a 35-m wide section of city walls occurred on January 31, 2014. The installed early-warning monitoring system is capable of an accurate and focused real-time displacement detection of the south-western side of the city including walls, buildings, and monuments, thus allowing prompt interventions for citizens safety and conservation purposes. The effectiveness of this alert technique became evident when the precursors of a second impressive wall collapse were clearly detected. From the beginning of the GBInSAR monitoring, we measured a constant displacement velocity of 0.1 mm/h in correspondence to a 15-m high wall sustaining the Acropolis and lying an underground parking. After a sudden increase of velocity values up to 1.7 mm/h, the local authorities were alerted so that they had time to interdict the area to citizens and to take adequate safety countermeasures two days before the collapse.**

***Index Terms*—Interferometry, monitoring, remote sensing, synthetic aperture radar.**

I. Introduction

In the field of cultural heritage preservation, it is essential to continuously supervise the stability condition of monuments, especially when density and complexity of the structures make a rationale and cost-effective plan of conservation works more difficult. Furthermore, a disadvantageous geo-morphological context associated with strong and unexpected meteorological occurrences requires, in addition to usual supervision and conservation activities, real-time monitoring in order to guarantee safety of inhabitants, visitors, and operators. According to these motivations, monitoring systems at monument or entire site scale have to provide a wide look angle associated to detailed imaging capability in order to cover a large area with metric or submetric resolution. At the same time, in case of contexts affected by geo-hazards or forthcoming structural collapses, a device working continuously, automatically, and without the need of physical interferences with the observed scenario is fundamental.

Many Italian heritage sites suffer from the consequences of ground instability, often related to bad weather conditions and the lack of routine maintenance. In particular, a lot of episodes related to heavy rainfalls leading to partial or total failures of historical structures occurred in Tuscany Region during the last years. Hence this territory can be reasonably considered a prime example of how preservation of heritage built environment represents a difficult task. In this area, conservators have often to deal with the extension of the area and the need of getting localized and real-time information in order to plan prompt and focused countermeasures. Therefore, the conspicuous number of exposed elements of high technical and artistic-cultural value requires strategies and systems capable of both monitoring instability phenomena and efficiently addressing restoration works.

In recent years, interferometric synthetic aperture radar (InSAR) techniques, both space-borne and terrestrial, have shown their capabilities in providing precise measurements of ground displacement on earth surface thanks to their cost-effectiveness, great accuracy, high spatial resolution, and good temporal coverage and measurement sampling [1]–[4].

Ground-based synthetic aperture radar interferometry (GBInSAR) is a radar-based technique successfully employed to detect the evolution of natural processes such as landslides [5]–[7], volcanic activity [8]–[11], and dynamics of glaciers and snow-covered slopes [12], [13]. This technology allows two-dimensional (2-D) displacement maps of a wide scenario (i.e., few square kilometers) with metric or submetric resolution, submillimeter accuracy and sampling frequency of few minutes to be produced. Moreover, there is no need of artificial targets installed on the field especially when man-made objects are observed, thus implying no interference with eventual operators and no risks when buildings are reasonably recognized as prone to collapse. Furthermore, GBInSAR is an active monitoring system, it works continuously and independently from weather and lighting conditions and it can be remotely controlled.

Different from space-borne interferometric techniques, GBInSAR is characterized by a high degree of operative flexibility and instrument versatility, since it can measure even more rapid movements (displacements from few millimeters per day up to 1 or more meters per day), over very steep unstable slope, not visible from the satellite, and it permits to choose the best line of sight (LOS) for the analysis [14].

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In virtue of the above-mentioned advantages, ground-based SAR technology has been applied even to the field of structural monitoring [15]–[18] and in particular to cultural heritage preservation [19], [20].

In recent studies, displacement data, usually displayed in the classic 2-D plane and then non-immediately attributable to physical targets, have been associated to a point cloud generated by a terrestrial laser scanner (TLS) survey so that a three-dimensional (3-D) displacement map is obtained [20]. This methodology has been applied to assess the condition of a historical built environment, thus proving that the integrated use of both technologies can play a key role in the preservation of cultural heritage sites. On January 31, 2014, a 30-m width portion of 17th century AD walls aligned to the south-west edge of the ancient city of Volterra (Tuscany, Italy) suddenly ruined, and it fell in the underlying scarp (Fig. 1). On the site an early warning GBInSAR remote sensing system was installed, providing real time surveys integrated by high-resolution TLS reliefs for a more reliable target identification. Through these instruments, an evident condition of instability affecting a second portion of the walls was detected in time to alert the population. As soon as acceleration of displacements was measured by the GBInSAR, an immediate alert procedure was started, making local authorities to forbid the access to the area and start first remedial works few days before the total collapse of masonry structures.

II. Study Area

A. Geological Setting

The city of Volterra is located in Pisa Province (Tuscany Region, Italy) at 460 to 500 m above sea level on a tableland mainly made of Pliocenic (Zanclean-Middle Piacentian) sandy-clayey formations. The stratigraphic sequence consists of a thickness of marine clays ("Argille Azzurre") of Early-Middle Pliocene age, overlapped by cemented sandy deposits ("Sabbie di Villamagna") and calcarenites (locally known as "Panchina" stone) that represent the top of the succession as well as the main lythotype of the urban fabric (Fig. 1).

B. Wall Collapse on January 31, 2014

Volterra is widely known as one of the most important Etruscan settlements, which then developed as a medieval center. Nowadays, the city still appears to be almost wholly embraced by the medieval walls that replaced the much larger Etruscan ones. Many sections of the great Etruscan wall-enclosure, dating back to the 6th to 5th century BC, are partially preserved (about 1.5 km long), and represent an invaluable cultural heritage element [21]–[24]. Present fortifications are made by large roughly squared stone blocks of "Panchina" and are the result of significant and repeated restorations across time, from the middle age up to the now, especially during the 18th century AD [25], [26].

On January 31, 2014, a 35-m long and 9.5-m high portion of the surrounding medieval walls suddenly collapsed in the south-western side of Volterra wrecking Via Lungomura Pratini and ruining on the escarpment (Fig. 1). The failure has affected a wall section that embraces the city center laying bare the foundations of buildings of historical and architectural interest overlooking the destroyed road, among which Palazzo Stella, built in the 1930s. Different geotechnical properties of the stratigraphic sequence upon which buildings were built played an important role in triggering the collapse. Part of the palace and orthogonal walls are settled on a sandy embankment, derived from Villamagna sands. The water accumulated above the impermeable clayey layer and exerted a pressure within the upper erodible sands and calcarenites. As a result, the wall has played a sort of "coating," together with the intrinsic instability of the sandy embankment due to the undermining of the slope. During the last century, the stone work has been cemented, filling the patching holes and preventing the ground water to appropriately flow out of the wall ring. As a consequence, intense rainfall that affected the whole area during the last days of January increased the hydrostatic pressure behind the wall, finally leading to the collapse. Moreover, the already critical situation has been worsened by the old sewer system that characterizes the historical city center of Volterra. Thus, the main cause of the wall failure can be attributed to the presence of the sandy and incoherent terrain, where the historical buildings (e.g., Palazzo Stella) were built, made unstable by previous water infiltrations and finally induced to fail by the intense precipitation events. Nowadays, below the unstable wall corner there is a footpath with benches, the underground parking entrance, and a terminus bus station. A public park and the archeological site of Volterra Etruscan Acropolis are located above this segment of walls. Stonework, especially in the upper portion of the wall, is the result of the repeated interventions carried out during the past and it testifies the prone-to-collapse nature of the embankment. Uncontrolled overgrown vegetation and scarcity of drainage apparatus revealed lack of routine maintenance.

III. Remote Sensing Techniques and Applied Monitoring Methodology

A. Ground-Based Radar Interferometry

GBInSAR is a microwaves-based remote sensing technology capable of producing interferograms (2-D displacement maps) of an area with a high accuracy (less than 1 mm) and a high acquisition rate (few minutes). GBInSAR system has been recognized, over the last decades, as an useful tool for the assessment of ground, monuments and building displacements [5], [7], [20], [27], [28]. The capability of the sensor to provide information relative to large areas, in three dimensions and multitemporal condition represents an advantage in comparison with the traditional monitoring techniques based on punctual measures. The linear SAR (LISA) system is a GBInSAR developed by the Joint Research Centre (JRC) of the European Commission. The sensor, known as GBInSAR LISALab system, is characterized by high flexibility in terms of acquisition geometry, polarization, acquisition frequency, and handiness of installation with the maximum adaptability in any situation.

B. Characteristics and Parameters of the Installed GBInSAR System

The radar system employed to monitor Volterra city walls is composed of a coherent microwave trans-receiver unit working

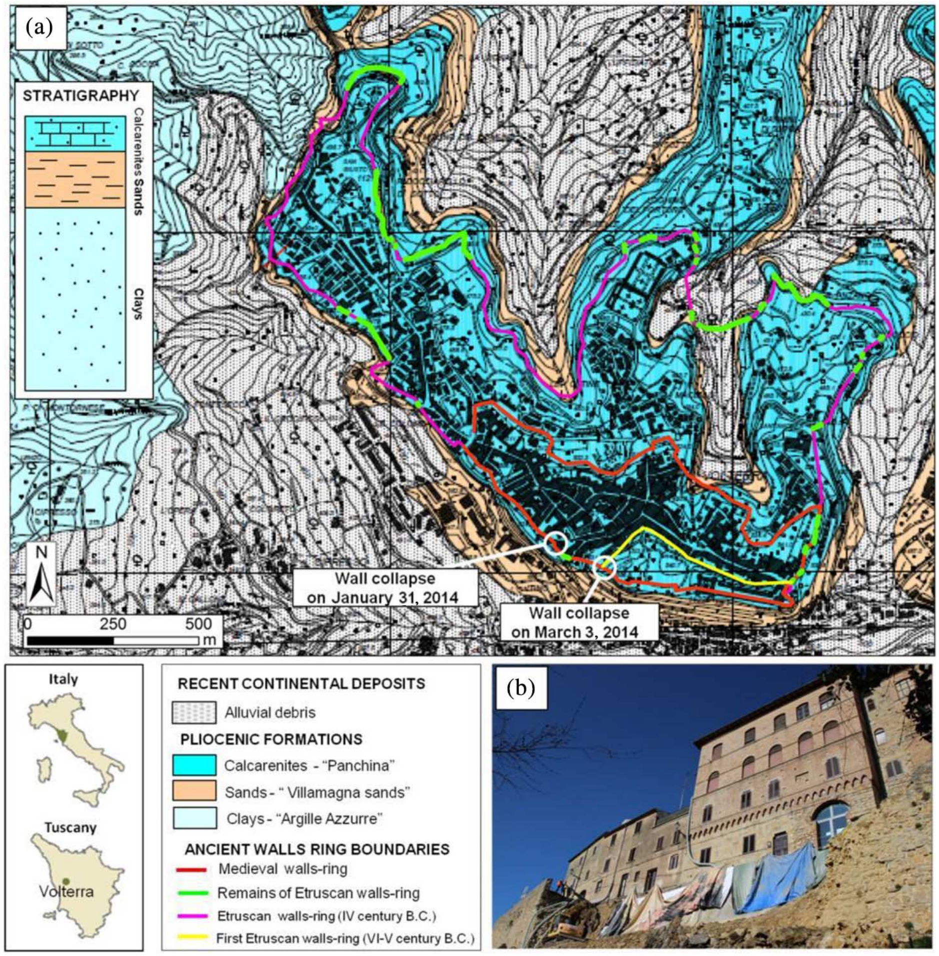

Fig. 1. Study area of Volterra. (a) Geographical and geological setting of the city area and mapping of original and remaining town-wall enclosures (Source: http://mapserver3.ldpgis.it/volterra/prg_ps/indagini_geotecniche.cfm, available from the web site: http://www.comune.volterra.pi.it/). (b) Photo of the wall collapse of January 31, 2014.

at Ku band with a bandwidth of 200 GHz and a central frequency of 17.2 GHz, generating a synthetic antenna about 3 m width [1], [2], [28]. The signal is then amplified and transmitted to the antennas. Synthetic aperture is realized by moving, via a linear positioner, a motorized sled hosting the radar head along a straight rail about 1.6 m of length. This system allows to reach a metric resolution and a submillimeter accuracy in displacement measurements. It is entirely controlled by a shock proof PC equipped with specific software that can be easily remote-controlled by every desk position. The radar field of view of about 60° allows the monitoring of a 800-m length wall section hit in the center of the first failure area. This system acquires an average of 180 images per day of the investigated scenario (an image every 8 min). The cross range resolution depends on the target distance, so that good acquisition geometries depend on the observed scene. In the center of the radar field of view, at a range distance of 600 m corresponding to the area of the January 31, 2014 wall collapse, range and cross range resolution are $0.75\,\mathrm{m} \times 1.75\,\mathrm{m}$, so that a single building-scale analysis is feasible. Interferograms span from 1 to 2 h baseline to monthly baseline in order to detect rapid and long-term movements. It is important to note that the system is able to measure only the component of the movement parallel the LOS of the instrument, thus the real displacement vector of the observed object can be calculated only if its direction is *a priori* known.

On February 19, 2014, we installed the GBInSAR instrumentation on the roof of a commercial building in the south-west surroundings of the city center. This location is stable and steady, as confirmed by recent satellite interferometric radar data that have been investigated before choosing the site. Persistent scatterer SAR interferometry (PSInSAR) (patented by [29]) data derived from COSMOSkyMed satellite and processed through SqueeSAR technique [30] show ground motion rates within the stable velocity range ($\pm 1.5\,\mathrm{mm/yr}$, displayed in green color in Fig. 2) on the installation site. The system, properly recovered in a log cabin in order to guarantee protection from atmospheric agents, is locked on a mechanical frame fixed to two concrete bases placed in the log cabin. Furthermore, some driving installation criteria have been followed: 1) an adequate sensor-target distance (about 600 m) aimed to guarantee an azimuth resolution spanning from 30 cm at 100-m range distance to 230 cm at 800-m range distance; 2) absence of obstacles between the radar sensor and the investigated objects; and 3) an installation surface not subjected to settling due to the weight of the cabin and radar equipment.

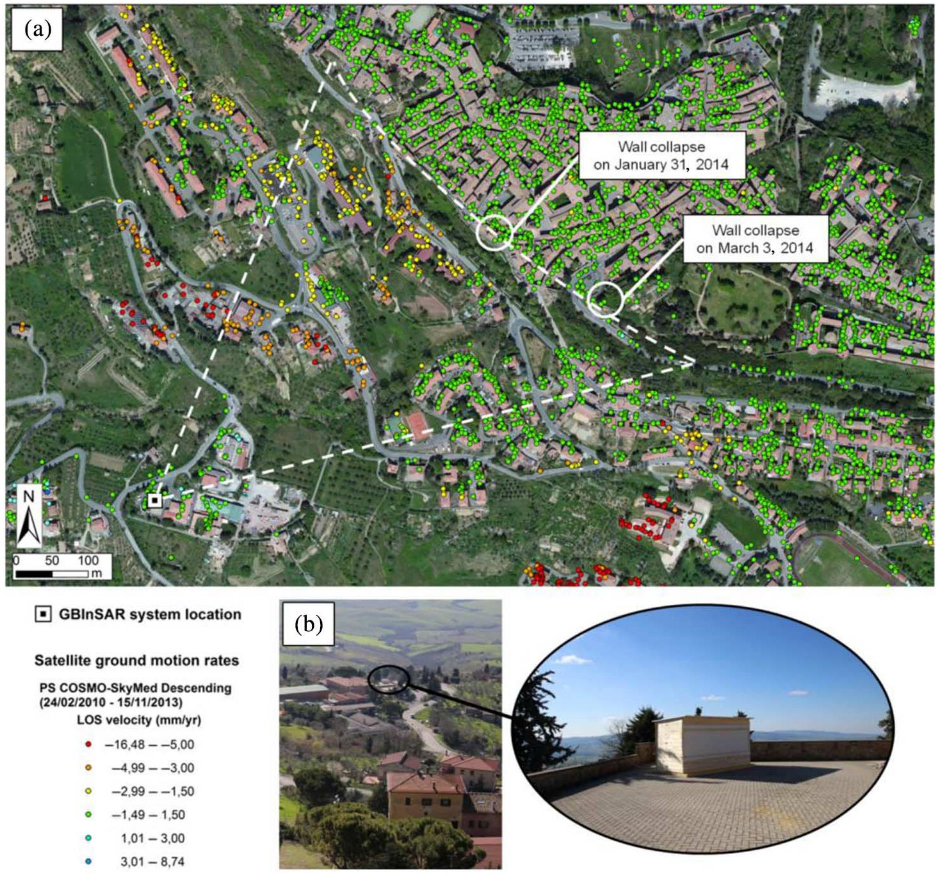

Fig. 2. Installation site of the GBInSAR. (a) PS velocity distribution map within Volterra south–west area using PS COSMO-SkyMed satellite data and radar field of view (white dotted line). (b) View of the GBInSAR from the medieval walls and a zoom (circle box) of the log cabin.

Moreover, because of the capability of the system to detect only displacement components along the LOS, we set the view direction as parallel as possible to the expected deformations.

C. Laser Scanner Reliefs and Integration With GBInSAR Displacement Measurements

TLS is a laser-based surveying instrument capable of generating automatically a 3-D digital model of the observed surfaces with an accuracy of few millimeters and high scan rate. The scanner gets the exact position of physical objects by measuring the laser time-of-flight between the sensor and the reflecting target. A point cloud characterized by (x, y, z) Cartesian coordinates and reflectance value R (x, y, z) is generated with an accuracy varying from 5 to 25 mm and a scan rate even less than 1–2 cm from long distances (hundreds of meters), meaning that this technique is noninvasive and suitable for nonaccessible or hazardous area.

TLS is widely used in the field of cultural heritage digital documentation for urban areas [31]–[34] single monuments [35]–[37], archeological sites [20], and single artworks [38]. High density of registered points, accuracy and noninvasiveness has made this technique suitable even for unstable slopes and rock cliffs monitoring applications [39]–[41]. In addition, by comparing surveys performed in different times, it is possible to infer the displacement occurred during the period between different acquisitions [42]. This technique has been successfully applied to civil and industrial structures [43]–[47] and unstable mountain slopes [48], [49].

Compared to GBInSAR, TLS does not suffer from those shortcomings such as loss of coherence, decorrelation, and displacement detection capability only along the LOS of the instrument. On the other hand, GBInSAR single measure can reach submillimeter accuracy, while using a TLS it is not possible to easily detect displacements smaller than 10 mm. As a consequence radar-based systems prove to be more suitable when high accuracy of the single measure is necessary, as in case of structural monitoring. Furthermore, an early warning system for near-to fail buildings requires a continuous work with a high scan rate and capability to operate in every weather or illumination condition. Typical TLS scan time has a magnitude order of tens of minutes, while a GBInSAR is able to complete an acquisition in few minutes. Moreover, the need to compare displacements of a huge number of points makes the TLS processing longer than the GBInSAR one. According to these considerations, the detection of movements on Volterra urban fabric has been performed only by using ground-based radar techniques. In addition, TLS has been employed to obtain a 3-D shape of the investigated scenario used as a spatial reference to display more realistically the displacement map resulting from GBInSAR surveys (Fig. 3). The advantage of such integration consists in facilitating the detection of the

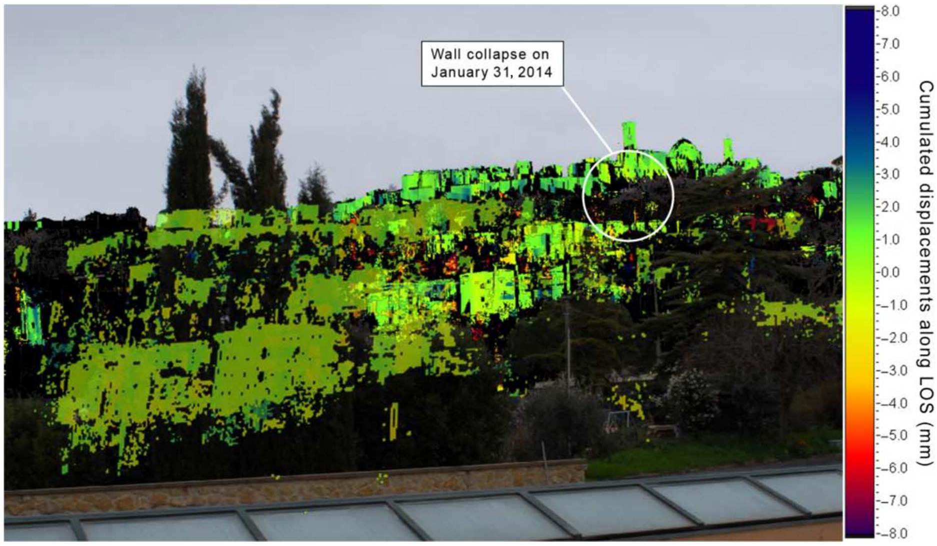

Fig. 3. 3-D radar point-cloud of cumulative LOS displacements measured by the GBInSAR from February 19, 2014 to September 16, 2014. Negative values refer to displacements toward the sensor; positive values refer to displacements away from the sensor.

exact object that is moving throughout the cumulated 2-D scene obtained by the merely ground-based radar data. Within the monitoring of natural processes (i.e., landslides), a high-detailed imaging capability is not necessary since a wide ground surface is moving. On the contrary, within monitoring in an urban environment each object can independently move and thus it is essential to discern a target to one another. A similar integrated use of GBInSAR and TLS technologies for monitoring purposes has been already proposed in the case of mountain flanks [13], urban sites [39], and cultural heritage sites [20].

In the framework of Volterra heritage structures monitoring, a 3-D laser scanner RIEGL LMSZ420-i [50] has been employed to obtain the 3-D shape of the investigated scenario. In order to cover shadowed surfaces determined by the irregular geometry of the buildings and the presence of obstacles (i.e., trees and electric lines) between the scanner and the targets, two surveys from different positions have been carried out: one from the same installation site of the GBInSAR cabin and the other one 180 m eastward. During the first acquisition even the Lisamobile instrumentation was scanned so that the exact position of the radar rail could be determined. Each point cloud has been then geo-referenced through reflectors installed on the scenario and used as reference points with the coordinates determined by a high-resolution topographic GPS. The final point cloud has been composed and geo-referenced using the dedicated software of the employed TLS [51]. At this stage, points not of interest (i.e., errors, vegetation, and electricity lines) were removed. Once obtained the exact coordinates of the radar instrumentation and of all the observed objects, the procedure exposed in [20] was carried out in order to associate each point of the point cloud to GBInSAR data. This results in a final product which takes advantage from the graphical information of a laser scanner survey and from the precision in measuring displacement typical of radar instruments. The entire procedure is automatic and managed by the radar processing software provided by LISALab.

IV. Results and Discussion

A. Results

On February 19, 2014, the GBInSAR system started scanning the southwest side of Volterra city walls. First radar power images immediately revealed the capability of the SAR imaging system of clearly displaying a wide portion of walls, the first row of buildings arising at the top of the fortification, some monuments emerging by virtue of their height (i.e., the tower of municipal hall, the bell-tower of the Dome and the Baptistery) and a lot of more recent structures situated between the radar and the walls.

From the beginning of the monitoring activity, a relative stability condition of the built environment was suggested by the absence of significant movements measured by GBInSAR system in the observed scenario with the exception of an area standing out for a significant linear displacement trend with a velocity of about 2 mm/day toward the sensor along the LOS direction (Fig. 4).

These values characterized a clear deformation pattern extended on the 2-D radar image 15 m in range and 25 m in azimuth corresponding to a 30-m width wall aligned to the intersection of Viale dei Ponti and Piazza Martiri della Libertà.

Velocity values measured by the GBInSAR system were maximum at the bottom of the wall and minimum at the top, suggesting a translational movement with a light rotational tendency typical of the loss in base support. This behavior is consistent with the collapse of a 30-m^2 cave (maximal internal height of 3.1 m excavated 10 m horizontally) situated below the walls and a portion of the Acropolis, the critical stability condition of which was detected during the days before the wall failure.

A relation between measured displacements and a structural criticality became undeniable on the basis of evident fissures perceived on the edge of the wall. First remedial works already undertaken consisted in a constrain system realized with steel frames aligned to the wall corners and steel

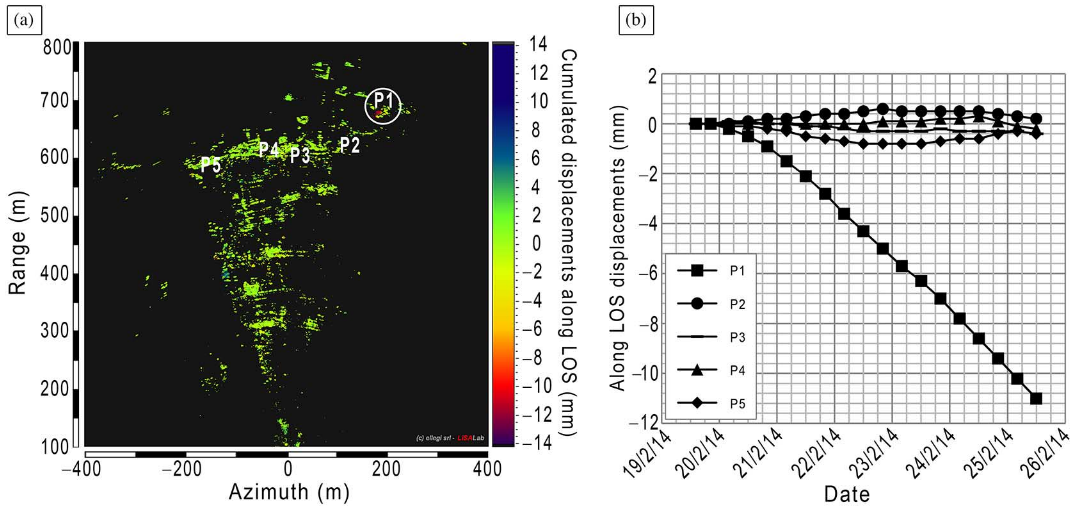

Fig. 4. Displacements measured by the GB-InSAR from February 19, 2014 to February 22, 2014. (a) 2-D radar map of cumulated displacements. The highlighted area (white circle) corresponds to the wall collapsed on March 3, 2014. (b) Cumulated displacement time series relative to control points indicated in (a). Negative values refer to displacements toward the sensor; positive values refer to displacements away from the sensor.

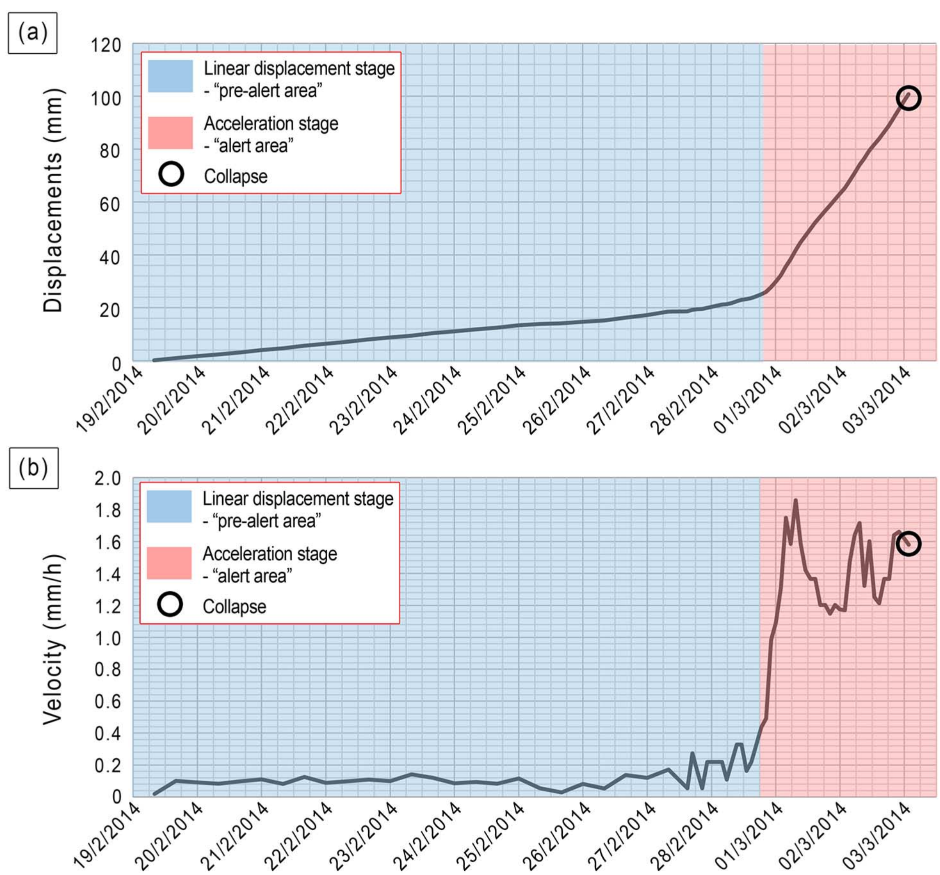

Fig. 5. GBInSAR measures relative to control point P1 (individuated in Fig. 4) set on the wall collapsed along Viale dei Ponti. (a) Displacements toward the sensor measured along the LOS from 14:10 of February 19, 2014 to 13:40 of March 3, 2014. (b) Displacements velocities toward the sensor measured along the LOS from 14:10 of February 19, 2014 to 13:40 of March 3, 2014.

cables anchored in the wall 7 m away from the corner on the north-west side and 20 m away from the corner on the opposite side. Further detailed inspections highlighted the presence of cracks in correspondence to cable anchors sites and an imminent-to-failure state of the upper portion of the wall not yet consolidated.

Displacement velocity during the first 9 days of monitoring remained stationary with a medium value of 2.2 mm/day.

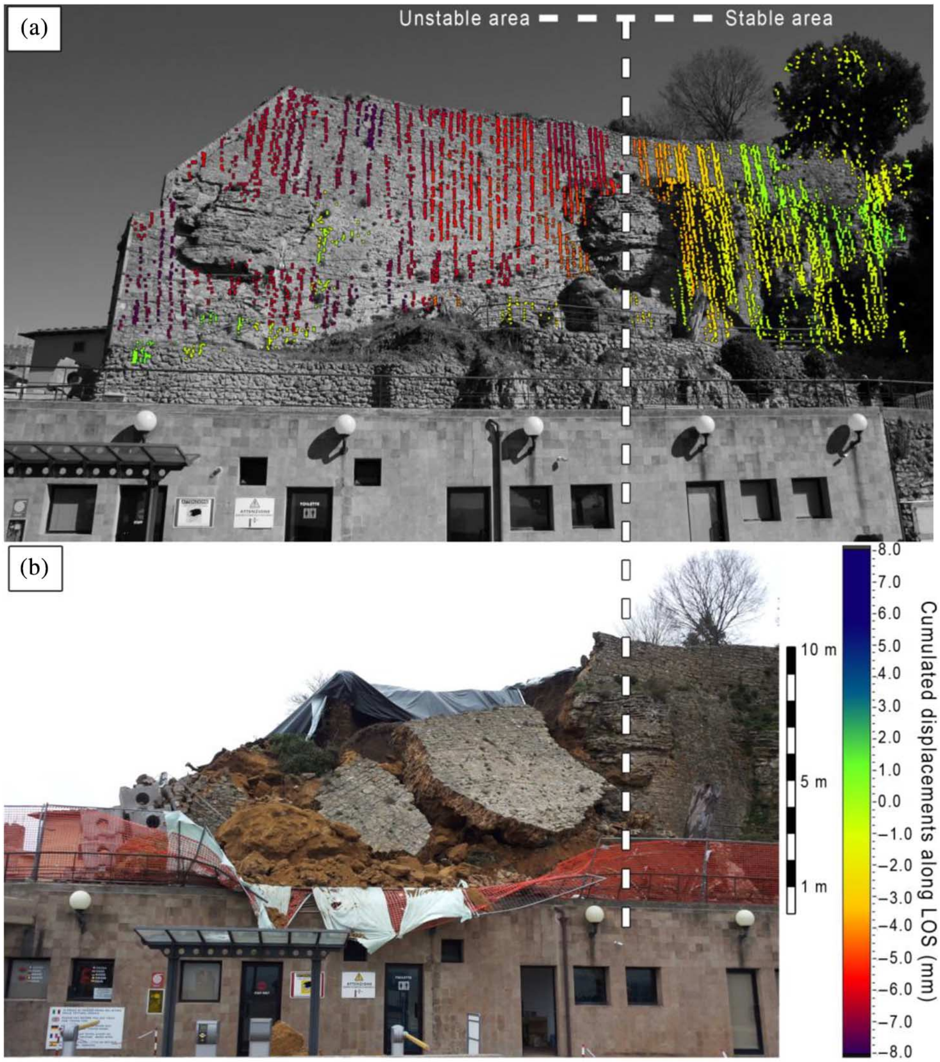

Fig. 6. Wall collapse along Viale dei Ponti. (a) Graphical superposition of the 3-D radar point-cloud relative to cumulate displacements along LOS measured by the GBInSAR from February 19, 2014 to February 22, 2014, on a photograph of the collapsing wall. Negative values refer to displacements toward the sensor; positive values refer to displacements away from the sensor. (b) Remains after the collapse of March 3, 2014.

According to information deduced from 2-D and 3-D radar displacement maps, authorities and conservators decided to start further inspections and remedial works in order to address stabilization works more efficaciously. Nevertheless, on the evening of February 27, 2014, a displacement of 4.11 mm was detected in a time span of 8 h. A second remarkable acceleration was registered on March 1, 2014, when a maximum velocity of 1.7 mm/h was reached (Fig. 5). These strong accelerations imposed to increase the monitoring rate using 2 h baseline interferograms. Although during the night between March 1, 2014 and March 2, 2014, velocity values decreased up to 1.2 mm/h, access to Piazza Martiri della Libertà, Viale dei Ponti, the Acropolis, and the underground parking was interdicted to citizens. Since the late morning of March 3, 2014, velocity increased once again up to 1.5 mm/h, remedial works concerning steel anchors were stopped and a rapid demolition of the upper part of the wall corner started. During these operations, in the afternoon of March 3, 2014, the wall completely collapsed (Fig. 6).

B. Discussion

GBInSAR monitoring activity undertaken in Volterra has been proved effective for conservation purposes of heritage urbanized areas affected by geological instability. Accuracy in displacement measures, achievable resolution, and high acquisition rate, lead to a detailed and real-time investigation of structural dynamics. On the other hand, some limitations related to the nature itself of the employed radar technology have to be considered during the planning phase of the monitoring campaign: 1) measured displacement refers only to the surface of the observed object that can be seen from the sensor; 2) only movements with direction parallel to the LOS of the instrument can be detected; 3) velocity underestimation due to phase wrapping is possible if the displacement rates exceed the threshold related to the wavelength of the emitted signal; and 4) in urbanized areas, many temporary high reflecting entities (i.e., the opening of doors and windows, the presence of moving vehicles and people) can interfere with measures or lead to misinterpretations or false alarms. Therefore the improvement of radar images interpretation capability of operators is fundamental to overcome such limitations. In addition, the definition of an efficient and fine-tuned monitoring procedure is essential to guarantee an effective early warning activity resulting in safety for people and prompt security measures for structures. Calibration of reference parameters and frequency of inspections is strictly related to the monitored phenomena. In the case of Volterra built environment expected occurrences mainly consist in sudden collapses of masonry structures. Since there were no previous monitoring to define stability thresholds, a routine activity has been planned to warn authorities about unstable structures defined as "alert areas." Areas affected by movements and previously not considered as being critical are classified as "pre-alert areas." These areas are characterized by displacement values greater than the expected accuracy of the instrument. For the definition of a "pre-alert area," further and deeper inspection of cumulated images (incremental method) and interferograms (rolling method) are required to overcome possible misinterpretations due to noise signal often recurring in urban areas as a consequence of human activities. Furthermore, on site surveys are essential to detect eventual visible fissures, humid surfaces, or cambers on structures. "Pre-alert areas" are then subjected to a higher rate of measurements, depending on the velocity of the investigated phenomena, and to a finer inspection of radar images (i.e., checking displacement time histories of defined control points), in order to obtain a focused analysis of structural dynamics and a detailed quantification of measured displacements. If further accelerations or relevant increase in displacements are measured, the "pre-alert area" is classified as "alert area" and warning procedures are started.

The proposed multilevel approach has been proved to be effective for the Viale dei Ponti wall collapse. In this case, accurate on-site inspection and deeper integrated GBInSAR measurements were carried out after the "pre-alert area" was individuated to inform and guide local authorities.

V. Conclusion

This paper describes the effectiveness of GBInSAR-based monitoring activities to analyze the structural stability of heritage built areas. A procedure which takes advantage from both InSAR and TLS technologies was tested for spatial and temporal analysis of wall failures affecting the S–W sector of Volterra (Tuscany, Italy). The joint use of accurate and frequent radar displacement measures and TLS imaging capability allowed us to detect structural criticality symptoms with adequate notice so that suitable countermeasures have been efficaciously addressed and alert and safety procedures have been promptly undertaken few days before the impressive wall collapse of Viale dei Ponti. In addition to the accuracy and resolution achievable with GBInSAR technology, the integration with geometrical information derived from TLS surveys simplifies the identification of observed objects and the interpretation of recorded movements. Indeed a more reliable relation between man-made structures and radar image has been definitely established only after the projection of the 2-D radar image (i.e., power image, interferogram, or cumulated displacements) on the 3-D point cloud generated by laser scanner reliefs. The final graphical product permits a detailed analysis of degradation processes involving ancient structures and it represents a simple-to-use radar-interpretation tool. Moreover, the multiple alert levels approach suitably adjusts to emergency contexts where it is fundamental to recognize criticalities and deliver alarm at the right time.

Results of the proposed monitoring and early warning activity achieved in Volterra encourage an extensive application to heritage sites characterized by unfavorable ground morphology, structural degradation and lack of maintenance. In these circumstances, and especially in the case of large areas to be managed, the use of technologies and methods described in this paper results in safety of citizens and in substantial advantages for restores and operators.

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